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Final Technical Report

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The following report describes the research efforts undertaken under this grant and explains our principal findings. Attachments include all available reprints and preprints of papers resulting from this work. Additional papers are in preparation and will be submitted later.

Technical Report

The AM Herculis (hereafter AM Her) objects are short orbital period ($P \sim$ hours), low mass ($M < 2\ M_{\odot}$) X-ray binary systems composed of a strongly magnetic ($B > 10^7$ G) white dwarf and a Roche-lobe filling late-type main sequence star. They are the strongest known white dwarf X-ray sources having X-ray luminosities of $10^{32} - 10^{33}$ ergs s^{-1} and bolometric luminosities of 10^{34} ergs s^{-1}. Their X-ray spectra are composed of two components. The soft X-ray ($E < 2$ keV) portions resemble blackbodies of temperature $kT_{bb} \sim 10$-50 eV while the hard X-ray ($E > 2$ keV) portions resemble optically thin bremsstrahlung spectra of temperature $kT_x \gtrsim 10$ keV. For a complete review of the observational properties of the AM Her objects see Liebert and Stockman (1984). For this grant, we have conducted several theoretical investigations concerned with the time variability of AM Her objects, and we have endeavored to use HEAO 1-A1 observations of these X-ray sources to test our theoretical models.

Physically, the nature of the AM Her objects is determined by the dwarf's large B-field. The B-field synchronizes the systems, prevents the formation of accretion disks, and forces field-aligned flows onto a fraction $f \ll 1$ of the dwarf's surface near its magnetic pole(s). The X-ray emission occurs when the funneled plasma strikes the dwarf and shocks, heating to temperatures of tens of keV. As the shock-heated plasma settles onto the dwarf, it cools by bremsstrahlung, optically thick thermal cyclotron emission, and

Compton cooling. The region in which the plasma cools and settles onto the dwarf is termed the "emission region." The dominant loss process in the emission region is determined by the white dwarf mass M_*, the "effective" accretion rate ($\dot{M}/f$), and the B-field. Bremsstrahlung produces the hard X-rays, while the blackbody limited cyclotron emission peaks in the optical or EUV. It is generally believed that the AM Her objects are bremsstrahlung dominated. The soft X-ray blackbody component is not produced in the emission region. It comes from the dwarf's surface being produced by the reprocessing of radiation from the emission region or is simply the intrinsic luminosity of the dwarf. For a more complete review of the theoretical properties of the AM Her objects see Lamb (1984).

Despite extensive research by many workers, the AM Her objects are still rather enigmatic. For example, when the observations of its most well observed member, AM Her, are compared to theory, the agreement is rather poor. The largest problem concerns the relative strengths of the hard and soft X-ray components. The "standard" theory assumes that the blackbody radiation is due to reprocessed bremsstrahlung, and so the ratio of the soft X-ray luminosity (L_s) to the hard X-ray luminosity (L_h) should be of order 1. In AM Her, the ratio is estimated to be anywhere from 5-100. The following explanations for this have been advanced: i) the electron scattering optical depth through the preshock flow is greater than 1 which implies that the bremsstrahlung spectrum is degraded as it traverses the preshock flow lowering L_h; ii) cyclotron emission is not negligible and so lowers the efficiency of bremsstrahlung emission, thus lowering L_h; iii) electron thermal conduction transports energy from the shocked plasma into the dwarf lowering L_h; and iv)

the accreted plasma undergoes steady nuclear burning in the dwarf's envelope enhancing L_s.

We have investigated the plausibility of items i), iii), and iv) by performing detailed steady state calculations of the emission region structures and of the effects of various preshock flow geometries on the emergent spectra. In calculations prior to ours (Aizu 1973; Katz 1977; Kylafis and Lamb 1979), spherically symmetric (SS) flows, equal electron and ion temperatures (a one-temperature approach), and negligible electron thermal conduction were assumed. We have refined these calculations in two ways: 1) in SS, we allow the ion and electron temperatures to differ (a two-temperature approach), include electron thermal conduction, and allow the accreted plasma to burn steadily (see Imamura et al. 1984a; and Weast et al. 1984); and 2) in a one-temperature approach without electron thermal conduction, we relax the assumption of SS by considering dipolar field aligned flow (see Imamura and Durisen 1983). Our work on item 1) with D. Q. Lamb and G. J. Weast was initiated in 1978. Although not directly funded by the grant, it has been continued in parallel with our funded research. Because of its usefulness to the grant-related investigations, we summarize it in the next two paragraphs. Our work on item 2) was undertaken specifically for the purposes of this grant and is described in subsequent paragraphs.

From an observational viewpoint, two-temperature and electron thermal conduction effects do not significantly alter the properties of accreting dwarfs over most of parameter space if the accreted plasma does not undergo steady nuclear burning. Only for $M_* > 1.3$ $M_\odot$ is a two-temperature approach required to calculate accurate luminosities and X-ray temperatures. In these cases, L_h is

increased by up to a factor of 1.5 and kT_x is decreased by up to a factor of 2. Concerning the emission region structures, however, two-temperature and electron thermal conduction effects are significant over a large portion of parameter space. For $M_* > 1.0$ $M_\odot$, a two-temperature approach with electron thermal conduction is required to calculate accurate emission region structures. We note that two-temperature and electron thermal conduction effects are important whenever Compton cooling is important. Further, we note that electron thermal conduction only transports energy around the emission region and does not act as a global loss mechanism. This means that electron thermal conduction is not the reason why $L_s/L_h \gg 1$.

If the accreted plasma is allowed to undergo steady nuclear burning, the blackbody luminosity of the dwarf is greatly increased. Typically L_{bb} increases by the factor

$$(QX\dot{M})/(GM_*\dot{M}/R_*) = 17(M_\odot/M_*)(R_*/5\text{x}10^8\text{cm})$$

where the denominator is the energy gained by the plasma falling into the dwarf's gravitational potential well and the numerator is the energy released by nuclear burning of the accreted plasma. The individual terms are G, the gravitational constant, Q, the energy released per gram in the proton-proton process, R_*, the white dwarf radius, and X, the hydrogen mass fraction of the plasma. The enhanced L_{bb} increases the radiation field in the emission region which enhances the effects of Compton cooling and therefore, two-temperature effects. When the accreted plasma undergoes steady nuclear burning, a two-temperature approach is required for an accurate treatment at all masses of interest. The major effects of

nuclear burning are to depress L_h and kT_x and to enhance L_s. The depressed kT_x makes nuclear burning models unattractive solutions to the AM Her dilemma because AM Her has kT_x = 31 keV, with an uncertainty of about 5 keV, while the hardest a nuclear burning dwarf can appear is about 26 keV (at M_* = 1.4 $M_\odot$). Thus, AM Her is only marginally consistent with these calculations.

Field-aligned flows tend to produce X-ray spectra which are quite similar to ones produced in SS calculations. However, the "funneling" does lead to: i) radiation escaping to infinity with a "fan beam" emission pattern; and ii) smaller electron scattering optical depths to infinity (τ_{es}) when compared to SS ones of the same effective accretion rate which leads to less degradation of the bremsstrahlung spectra. Concerning item i), we have used the "fan beam" emission patterns to calculate light curves magnetic white dwarfs in binary systems are likely to produce for a wide range of orbital inclinations and magnetic field orientations. The light curves are rather sensitive functions of these parameters and can be used to place constraints upon the geometry of AM Her's emission region. We are currently in the process of comparing our light curves to the observed light curves of AM Her. We had proposed to use HEAO 1-A1 data to generate additional light curves but were disappointed to find, after considerable effort, that the data were too noisy. Our light curves did not improve on others in the literature.

Using our theoretical models, we have also considered the question of the large L_s/L_h ratio (Imamura 1984). The calculations suggest that degradation of the bremsstrahlung can't explain the large L_s/L_h ratio in AM Her. To get the observed

ratios, requires that the degradation be very severe. The large degradation requires a large τ_{es} which has two problems: 1) it leads to $kT_x << 30$ keV; and 2) it implies that $\dot{M}/f \sim \dot{M}_E$ (or equivalently $f << 1$), which leads to $kT_{bb} >> 50$ eV. Here $\dot{M}_E$ ($=4\pi R_* c/\kappa_{es}$) is the Eddington accretion rate. Both of these results do not agree with the observations.

The previous discussion has assumed that a steady state model of the AM Her objects is reasonable. However, recent work, both theoretical and observational, suggests that AM Her objects may be variable. Observations of the AM Her objects AN UMa and E1405-451 have shown that they show coherent periodicities on time scales ranging from 1 to 2 seconds in their optical emission (Middleditch 1982). Middleditch suggests that these variations are due to the oscillatory instability of the emission region structures found by Langer, Chanmugam, and Shaviv (1981,1982) and Langer (1984) during time-dependent calculations of accretion flows onto magnetic white dwarfs. Langer et al. found that one-temperature shocks with power law cooling functions proportional to $\rho^2 T^\alpha$ are unstable to oscillatory motions whenever $\alpha < 0.6$. Because AM Her shocks are probably bremsstrahlung dominated (i.e., $\alpha = 0.5$), Langer et al. suggested that they are likely candidates to show this instability. They predict that the oscillations will occur with time scales on the order of three times the postshock plasma cooling time scale (t_{cool}), which ranges from tenths of a second to several seconds, consistent with the observations of Middleditch. However, because Middleditch observed the periodicities in the optical it is not clear that the variations reflect variations in the emission region structure. The optical emission is not produced in the emission

region. It probably arises from a region higher up in the preshock funnel.

To further the understanding of the nature of the periodicities seen by Middleditch, we have also studied the stability properties of the emission regions. Our calculations differ from Langer et al.'s in that we consider SS flows, and we use a two-temperature approach with electron thermal conduction and Compton cooling in some of our calculations (see Imamura et al. 1984b,c). With regard to the different geometries, the differences are small because the thicknesses of the emission regions are always much less than R_{*}. Our results qualitatively agree with Langer et al., but differ in detail. We find that: i) several oscillatory modes are possible, which we call in order of increasing oscillation frequency the Fundamental (F), the First Overtone (1O), the Second Overtone (2O), and so on; ii) the F, 1O, and 2O are unstable for $\alpha < 0.4$, 0.8, and 0.8; iii) the F, 1O, and 2O have oscillation periods of $3t_{cool}$, $5/3t_{cool}$, and t_{cool}; iv) for bremsstrahlung dominated shocks (i.e., $\alpha = 0.5$), there will be periodicities on the time scales $5/3t_{cool}$ and t_{cool} with fractional luminosity variations of up to 50%; and v) for accretion onto a 1.0 $M_{\odot}$ white dwarf, the inclusion of two-temperature effects, electron thermal conduction, and Compton cooling stabilizes all oscillatory modes. The results of our nonlinear calculations are in excellent agreement with the linear analysis of Chevalier and Imamura (1982). Langer et al. appear to see the F but no overtones. We do not have an explanation for this discrepancy.

Observing this instability would be quite valuable because t_{cool}, being approximately given by

$$t_{cool} = I/(\Lambda_0 \rho^2 T^{1/2}) = 0.012(\dot{M}_E f/\dot{M})(M_*/M_\odot) \text{ seconds,}$$

is a function of the effective accretion rate and the depth of the dwarf's gravitational potential well. In the estimate for t_{cool}, I is the specific internal energy, $\Lambda_0 \rho^2 T^{1/2}$ is the bremsstrahlung volume emissivity, and we have used the Rankine-Hugoniot strong shock jump conditions to define typical postshock plasma conditions. Thus, if $\dot{M}/f$ is known, a direct determination of the dwarf's gravitational potential can be made. Further, if one assumes a white dwarf mass-radius relationship (see Chandrasekhar 1957), the mass and radius of the dwarf can be separately determined.

We are currently in the process of analyzing pointed data of AM Her taken by the HEAO 1-A1 experiment. The A1 experiment was sensitive to photons in the energy range 0.5-20 keV and had a temporal resolution of 5 ms, so in principle, variations in the emission region structure would be expected to show up in the data. However, because AM Her shows substantial "flickering" on time scales of tens of seconds and the signal to noise ratio (S/N) of the time-averaged data is ~ 1, the detection of low amplitude, short period coherent fluctuations is difficult. We are currently in the process of searching for periodicities in the A1 data using Fourier techniques.

To summarize, we have made several useful and important contributions to our theoretical understanding of X-ray variability in AM Her objects. We have generated funneled accretion models that make detailed predictions of X-ray light curves (Imamura and Durisen 1983). When applied to real systems, they constrain various geometrical and physical parameters (Imamura 1984). The same funneled accretion models have provided useful tests of various explanations for the

large observed L_s/L_h (Imamura 1984). We have also investigated the oscillatory stability of the postshock regions of white dwarf accretion flows (Imamura et al. 1984b,c). Unfortunately, the HEAO 1-A1 scan data did not yield quality light curves for comparison with our funneled accretion models, but we are now in the process of Fourier analyzing pointed data in the hopes of detecting evidence for shock oscillations.

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Grant-Related Publications

Published

Imamura, J. N. and Durisen, R. H. 1983, "X-ray Spectra and Light Curves of Accreting Magnetic Degenerate Dwarfs," The Astrophysical Journal, 268, 291. Reprint attached.

In Press

Imamura, J. N., Chevalier, R. A., Durisen, R. H., and Wolff, M. T. 1984, "Stability of Radiative Shock Waves," in Proceedings of H. E. A. D. Workshop on Cataclysmic Variables and Low Mass X-ray Binaries, eds. D. Q. Lamb and J. Patterson, (Dordrecht: Reidel). Preprint attached.

Imamura, J. N., Wolff, M. T., and Durisen, R. H. 1984, "Numerical Studies of the Stability of Radiative Shocks," The Astrophysical Journal, 276. Preprint attached.

In Preparation

Imamura, J. N. 1984, "Comparison of Funneled Accretion Models with Observations of AM Herculis Objects," The Astrophysical Journal.

We also plan to have a publication on the Fourier analysis of HEAO 1-A1 data.